MSL/MASTCAM IN-FLIGHT CALIBRATED IMAGES: AN IMPROVED DATASET OF RADIANCE AND REFLECTANCE IMAGE PRODUCTS FOR THE PLANETARY DATA SYSTEM.

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Introduction: The Mast Camera (Mastcam) instrument suite on the NASA Mars Science Laboratory (MSL) Curiosity rover consists of two CCD cameras, a 34 mm focal length (20° x 15° field of view) left "eye" and a 100 mm focal length (6.8° x 5.1° field of view) right eye camera, that are each capable of providing Bayer color and narrow-band multispectral imaging through the use of an eight-position filter wheel [1,2]. These instruments have acquired tens of thousands of observations over approximately two thousand mission sols (a sol is a martian day), providing an extensive dataset of rock, soil, and other imaging targets along the rover traverse within Gale crater, Mars.

Comparisons of visible to near-infrared absolute reflectivity and spectral properties rely on accurate calibration to convert from raw data number (DN) values to meaningful radiometric quantities, such as radiance (*e.g.*, $W/m^2/nm/sr$) and radiance factor (or "*I/F*", where *I* is the scene radiance and πF is the incoming solar irradiance). The latter quantity can be compared directly to laboratory-measured bidirectional reflectance spectra of analog minerals or mixtures to make inferences about compositional variations of materials observed by the cameras (*e.g.*, [3,4,5,6]).

At present, the Reduced Data Records (RDRs) being archived in NASA's Planetary Data System (PDS) for Mastcam make use of an initial pre-flight calibration that is not optimized for scientific analyses requiring high fidelity radiometric calibration. The PDS "DRXX" products include corrections for bias, dark current, and pixel-to-pixel responsivity variations in the detector derived from pre-flight calibration images. That *I/F* calibration is derived from the ratio of the calibrated, observed DN values to an expected DN that would be measured by imaging a perfectly diffuse, white surface at zero incidence angle, under solar illumination, at the perihelion distance of Mars (with no atmospheric attenuation), and relative to a reference exposure time of 10 msec [1,7].

Considerable improvements to radiometric accuracy can be achieved by the inclusion of additional pre-flight and in-flight calibration models and data. Most significantly, the majority of the multi-filter image sequences acquired by the rover were accompanied by near-in-time observations of the onboard Mastcam calibration target ("caltarget"), composed of materials with known reflectance properties. Observations of the caltarget can be used to derive *I/F* values that more accurately account for atmospheric scattering and absorption of incident sunlight through the martian atmosphere. Details of this correction, as well as other improvements, are discussed below.

We are in the process of producing radiance and *I/F*-calibrated Mastcam RDRs that include the latest pre-flight and in-flight improvements to the radiometric calibration. These will be submitted to the PDS, along with documentation, in stages beginning mid-2018. Each product will have both an attached ODL label (consistent with PDS3 format) and a detached XML label (consistent with PDS4 format) containing the observation metadata. These releases will initially include Mastcam data spanning sol ranges that have already been released to the PDS, until complete; further releases may extend this dataset following MSL mission data releases.

Methodology: The RDRs will be generated by means of an improved calibration pipeline outlined in Figure 1 [1]. The differences from the currently-archived "Version 1" PDS RDR products are as follows:

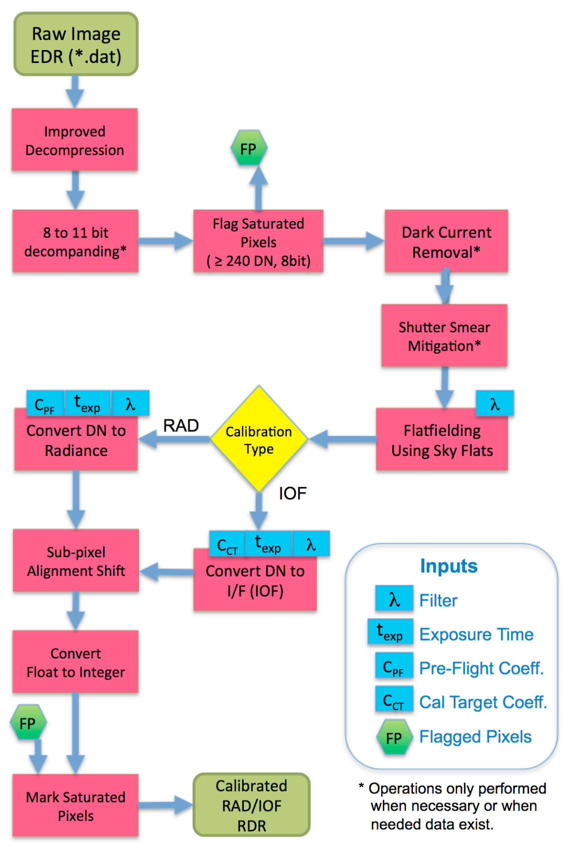

Figure 1: Flowchart describing an improved calibration pipeline for Mastcam data [1].

Improved demosaicing. All Mastcam images are acquired through a Bayer microfilter array (composed of a 2x2 unit cell of red, green, and blue pixels) directly bonded to the CCD. Many broadband (RGB) images are downlinked after having been compressed with lossy JPEG compression algorithms; in these cases, color interpolation is done on-board the rover using Improved Linear Interpolation (ILI), also known as Malvar-He-Cutler demosaicing [8]. For images that are returned raw or losslessly compressed, it is possible to choose a different debayering method. We have found that using another algorithm known as Directional Linear Minimum Mean Square-Error Estimation (DLMMSE, or Zhang-Wu demosaicing [9]) often produces better results, with fewer color artifacts.

Flagging of saturated pixels. Autoexposure algorithms used to set exposure time during image acquisition can still result in a very small percentage of overexposed pixels or pixel values that exceed the CCD linearity range. Small, bright features that contrast strongly with the surrounding material in the field of view can result in an image with saturation on surfaces that may be of interest to an end user. However, because such pixels cannot be accurately radiometrically calibrated, we flag them to prevent their inadvertent use in analyses. Flagged pixels are set to a value indicated in the label.

Correction for electronic shutter smear. Shutter smear, the added signal that results from light leakage into the CCD vertical shift registers during readout, is generally a minor contribution to the measured signal [1]. It can be corrected for in a straightforward manner by subtracting a zero second exposure image acquired of the same target at nearly the same time. Such an image is almost never acquired, however, and therefore it is desirable to model the smear for instances in which it might be desirable or necessary to correct for it. We are exploring ways to model and subtract the smear component from the data using the scene signal and an understanding of the CCD readout process.

Improved flat-fielding. In-flight images acquired of the cloudless martian sky in the anti-sunward direction have been used to produce an updated set of flat-field images [1]. These are preferable to the pre-flight flat-field observations because they include any subsequent changes in pixel-to-pixel response that have occurred since pre-flight testing (due to, *e.g.,* dust accumulation on the front camera window). Our improved calibration pipeline will include these and any updates from subsequent in-flight monitoring.

Accurate radiance calibration. Radiance calibration coefficients derived from pre-flight measurements of a NIST-calibrated integrating sphere [1] can be used to convert DN values to more accurate estimates of radiance. These values show good agreement with coefficients derived from radiative transfer modeling of Mastcam sky imaging, with the exception of the shortest wavelength (445 nm) filters (Table 11 of [1]). For those two filters, the sky-model coefficients are believed to be more accurate, due to significantly lower signal-to-noise present in the pre-flight measurements of the calibration lamp at those wavelengths. Our radiance-calibrated products will substitute those coefficients for radiometric calibration of the 445 nm “L2” and “R2” filters, otherwise making use of the pre-flight calibration data.

In-flight-derived I/F calibration. As mentioned in the introduction, *Curiosity* carries a calibration target on the rover deck designed to allow accurate *I/F* calibration. Three grayscale rings and four corner color chips provide surfaces with well-characterized reflectance properties; sweep magnets under two of the rings and each of the color chips deflect dust around a small circular area above each magnet. Measured radiances of these surfaces can be fit against the laboratory-measured reflectance values to derive calibration coefficients. A significant complication is the deposition of airfall dust on the surface of the caltarget, which substantially alters the reflectance values from that of the clean substrate materials. We account for this by means of a two-layer scattering model [1] (*cf.*, also, [10,11]), which derives the incoming radiance and the opacity of the dust layer. Caltarget images are frequently acquired in a matching filter set with most multispectral observations; details of which caltarget is used, the difference in time between it and the observation it calibrates, and a quality flag related to that time difference will be included in our *I/F* RDR labels.

Conclusions: PDS archiving of more robustly calibrated Mastcam RDRs will provide a widely accessible dataset for quantitative radiometric analyses. These products can be used to support a variety of photometric and spectral studies and augment the results of other rover instrument datasets, enabling a better understanding of the geologic and environmental history of the site.

References: [1] Bell, J.F., III *et al.*, *Earth Space Sci., 4,* 396, 2017. [2] Malin, M.C. *et al.*, *Earth Space Sci., 4,* 506, 2017. [3] Wellington, D.F. *et al.*, *Am. Min., 102*, 1202, 2017. [4] Johnson, J.R. *et al.*, *JGR, 122,* 2017. [5] Horgan, B. *et al.*, *LPSC XLVIII*, #3021, 2017. [6] Fraeman, A.A. *et al.*, *LPSC XLVIII*, #2185, 2017. [7] Caplinger, M., MSSS MSL Cal. Summary; http://pds-imaging.jpl.nasa.gov/data/msl/MSLMST_0008/CALIB/MSL_MMM_CAL.TXT, 2013. [8] Malvar, H.S. *et al.*, *ICASSP, IEEE, 3*, 485, 2004. [9] Zhang, L. & Wu, X., *IEEE Trans.Signal Proc., 14,* 2167, 2005. [10] Bell, J.F. III *et al.*, *JGR, 111,* E02S03, 2006. [11] Kinch, K.M. *et al.*, *Earth Space Sci., 2,* 144, 2015.

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